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Characterising the Performance of Selected Electrical Machine Insulation Systems

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Abstract— This paper presents results from an analysis of alternative slot liner materials used in the construction of electrical machines. The slot liner material has a vital safety critical function within a machine assembly, providing electrical insulation between the winding body and stator core pack. Performance measures for the slot liner material include the dielectric breakdown voltage, tensile strength, thermal conductivity and thermal class, amongst others. There is a large variety of slot liner materials available on the market with the material properties altered to suit a particular application. Some of these material properties are strongly dependent on the components and processes employed in construction of the complete winding assembly e.g. type of the winding impregnation and/or method used in impregnation of the stator/winding assembly. Consequently, the manufacturer provided data is usually inadequate when comparing various insulation systems and their individual elements for a particular machine construction. This research is focused on the conductive heat transfer phenomenon from the winding body into the machine periphery in context of the slot liner material used, for a given impregnation type and method. The repeatability of the winding manufacture process is also investigated. Three alternative slot liner materials with different thermal conductivity and ability of absorbing varnish impregnation have been chosen for prototyping of representative stator/winding hardware exemplars. This has been supplemented with a batch manufacture of the stator-winding hardware exemplar for a selected slot liner material. The proposed experimental approach allows for the complete insulation system to be evaluated accounting for the assembly and manufacture nuances. The results suggest that the use of a particular slot liner has an impact on the winding heat transfer and also implications regarding appropriate manufacture and assembly processes used, i.e. some of the materials require special handling. The experimental work has been supplemented with theoretical analysis to provide a more comprehensive insight into the winding heat transfer phenomena.

Keywords—low-voltage electrical insulation system, slot liner material, manufacture repeatability, heat transfer;

I. INTRODUCTION

The continuous drive towards compact high-performance electrical machine solutions has resulted in an increasing need for a more comprehensive thermal design-analysis approach, where various design, manufacture and assembly parameters

are accounted for. These factors have a significant impact on a machine's thermal behaviour and usually require experimental methods to validate the initial design assumptions. The stator-winding assembly is particularly challenging in this context as it consists of various material types and uses several manufacturing processes. Also, the power loss generated within the winding body is one of the main heat sources in an electrical machine. Therefore, providing a design solution with 'low' power loss and 'good' dissipative heat transfer capability is very desirable. There is a wide body of work focusing on both design aspects including various winding constructions with 'low' power loss generation, e.g. high-speed/high-frequency applications [1]-[9] and winding impregnation and cooling mechanisms to provide 'good' heat extraction from the winding body, e.g. automotive and aerospace applications [10]-[18].

In this paper, the latter design aspect is investigated, in particular the use of various electrical insulation materials for the winding assembly. The electrical insulation system used in construction of the stator-winding assembly has an important role of separating the winding conductors/turns from each other and winding body from the stator core pack. Simultaneously, it should provide 'good' heat transfer from the winding into the machine periphery, typically. The separation between the winding and stator core is usually assured by the suitable slot liner material together with winding impregnation. The available slot liners are usually in the form of film or paper-like sheets, which are formed to size and fitted together with the winding within slots of the stator assembly. In some applications the slot lining is realised by an appropriate powder coating of the complete stator core pack. The slot liner and impregnation materials interact during the winding impregnation process altering the thermal properties for the complete stator-winding assembly, i.e. while the impregnation material penetrates and fills-in cavities within the stator-winding assembly, the slot liner material absorbs some of the impregnation. The overall heat transfer from the winding body into the stator core and machine periphery is strongly affected by the insulating/impregnating materials as well as the manufacture and assembly processes used. Assuring a reliable process, where the stator-winding performance measures are repeatable in volume manufacture is the other important aspect in the design-development of electrical machines. These design issues are usually treated

during the ‘design for manufacture’ and ‘design for performance’ stages of the development process. In this paper, the use of various slot lining materials and repeatability of the manufacture and assembly of the stator-winding assembly is investigated. A number of representative stator-winding exemplars have been manufactured and tested including more absorbent slot liner materials, which potentially provide an improved heat transfer from the winding body into the machine periphery. However, as this type of slot liner material has usually lower ratings in terms of dielectric breakdown voltage and tensile strength, careful consideration must be given to selecting the material to satisfy the application and manufacture/assembly requirements. Also, the experimental data from the manufacture repeatability tests indicates that a degree of discrepancy in performance measures between theoretically identical formed samples exists. Consequently, for volume manufacturing appropriate manufacture quality check needs to be in place to ensure final product conformance measures within the manufacture/performance tolerances or limits.

The experimental work presented in the paper has been complemented with theoretical analysis to provide a more comprehensive insight into the heat transfer phenomena from the winding body into the machine periphery. In particular, the interface thermal resistance between the winding body, slot liner and laminated core pack has been investigated. This is especially important as the application of ‘better’ materials, e.g. slot liner and/or impregnation materials with improved thermal conductivity might not yield expected performance gains if is not supplemented with appropriate manufacture and assembly processes. Also, in the analysed case the theoretical predictions have confirmed that the winding-to-slot interface thermal resistance has a significant impact on the heat transfer from the winding body. This issue has also been reported by other authors [15], [16], [19]. As the slot interface thermal resistance is notoriously difficult to predict theoretically, thermal design of a machine without any experimental data or previous experience might be challenging and ultimately inaccurate. Detailed discussion regarding the outcomes of experimental and theoretical work has been provided in the latter section of the paper.

II. TEST SAMPLE CONSTRUCTION

To evaluate the use of alternative slot liner materials and repeatability of the manufacture processes used in the construction of the stator-winding assembly, a number of representative hardware exemplars have been produced. An individual hardware exemplar (motorette) consists of an open-slot solid steel stator core, a preformed coil representative of a single-layer concentrated wound winding, slot liner and slot closure/wedge, Fig. 1. The preformed coil is manufactured using compacted Type-8 Litz wire providing a high conductor fill factor. The motorette’s slot geometry is identical to that of a brushless PM machine, which is currently in the prototyping stage of the development cycle. Some of the machine characteristics include: radial-flux topology, surface mounted PM rotor assembly, forced air-cooled housing and high torque-density with targeted continuous specific torque capability of the machine exceeding 20Nm/kg, based on the weight of the active stator and rotor elements.

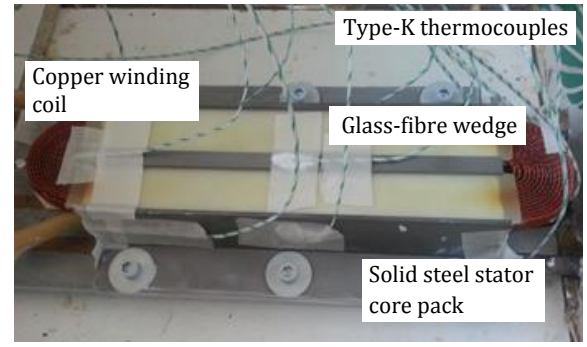


Fig. 1. Test sample (motorette) prior to impregnation

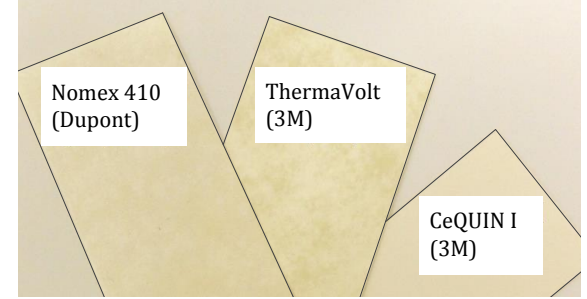


Fig. 2. Samples of the slot liner materials used in the analysis

TABLE I. BASIC SLOT LINER MATERIAL DATA

Property	Nomex 410 (Dupont)	ThermaVolt (3M)	CeQUIN I (3M)
Thickness [mm]	0.25	0.25	0.25
Basis weight [kg/m ²]	0.249	0.366	0.270
Dielectric breakdown voltage ¹⁾ [kV]	8.25	5.0	1.8
Tensile strength ²⁾ [kN/m]	29.6/16.1	9.3/6.0	2.1/0.7
Thermal conductivity @ 180°C [W/m·K]	0.139	0.230	0.195
Insulation class	R (220°C)	R (220°C)	R (220°C)

¹⁾ ASTM D-149 standard test method;

²⁾ Fibre machine direction of paper/across fibre direction of paper.

Both the winding coil and stator core are instrumented with several Type-K thermocouples. In total there are 14 thermocouples located in the winding and stator core allowing for the heat transfer/thermal resistance across various paths to be determined. The complete and fully instrumented winding test sample is vacuum impregnated using solvent based varnish (Elmotherm 073-1010 by Elantas) and then cured/baked according to the varnish manufacturer data sheet (8 hours at 160°C). Three alternative slot liner materials have been considered here, which are characterised by different thermal conductivity and their ability to absorb the impregnation material, amongst other requirements. The ability to absorb the impregnation material is particularly relevant to the quality of the heat transfer from the winding body into the stator core pack. It is expected that a material with a ‘good’ absorption factor will provide reduced thermal resistance across the stator-winding interface as compared with more commonly used slot liner materials. Samples of the materials used are shown in Fig. 2, and basic material data is listed in Table I. The complete set

of material physical properties is available on the manufactures online material data repository [21], [22].

When analysing the basic material data, it is evident that ThermaVolt has the highest thermal conductivity among the analysed materials, which is also reflected in its higher density. CeQUIN I is a highly absorbent material, which requires impregnation to achieve its full physical properties. Although the stated thermal conductivity of CeQUIN I is lower than ThermaVolt, the total insulation system thermal conductivity may be higher for CeQUIN I due to improved penetration of the impregnation material. Nomex 410 has the highest dielectric breakdown voltage and tensile strength for the set of analysed materials. Both ThermaVolt and CeQUIN I are categorised as inorganic liners, whereas Nomex 410 belongs to the group of organic linear materials. CeQUIN I has the highest inorganic-content for the analysed material samples and is primarily composed of glass fibres and microfibers, inorganic fillers, and less than 10% organic binders. Due to high glass fibre content it is recommended to handle the material in gloves to prevent skin irritation. The inorganic liner materials have low moisture absorption and high long-term dielectric strength. However, they suffer from reduced mechanical strength, which is particularly important in the manufacture and assembly processes. Throughout the assembly of a number of motorettes, it has been found that CeQUIN I is the most ‘fragile’ from the group of liner materials considered. As a result of the reduced mechanical strength, both CeQUIN I and ThermaVolt are well suited for a ‘single stage assembly’, where repeated mechanical stress associated with winding or conductors insertion is limited, e.g. placement of the preformed winding coil analysed in this research. Conversely, Nomex 410 has been found to be very robust allowing for repeatable conductor insertion, e.g. ‘winding in situ’ where the winding is wound on the stator core pack. Due its organic composition Nomex 410 should be stored sealed to prevent moisture absorption.

III. EXPERIMENTAL SETUP AND TESTING PROCEDURE

An experimental approach has been used to assess influence of various slot linear materials on the conductive heat transfer across the stator-winding interface. The experimental set-up consists of a thermally insulated chamber, liquid-cooled temperature-controlled cold plate, data acquisition system and dc power supply, Fig. 3. A hardware exemplar sample is mounted on the cold-plate and placed in the chamber prior to tests. The cold plate temperature is fixed at 15°C during the tests. Such a set-up allows for controlled and repeatable testing conditions with the main heat path being the winding body to the heatsinked stator core. The thermally insulated chamber assures adiabatic-like conditions for the sample surfaces, which are not in contact with the cold-plate. The coil winding is energised from a dc power supply for a set of current levels. When the motorette sample reaches thermal equilibrium at a given excitation, the current is increased and thermal test is repeated until the thermal limit of the insulation system is reached. The power loss and temperatures within the hardware sample and cold plate are monitored and logged during the tests. The testing procedure has also been used to evaluate repeatability of the manufacture

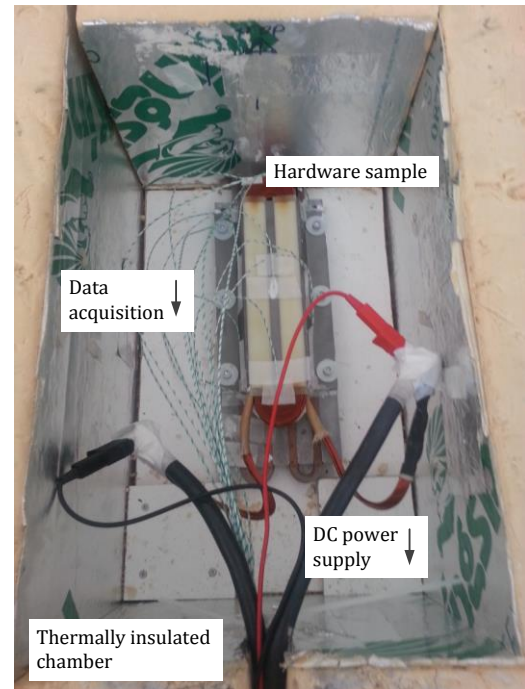


Fig. 3. Experimental setup for dc thermal tests

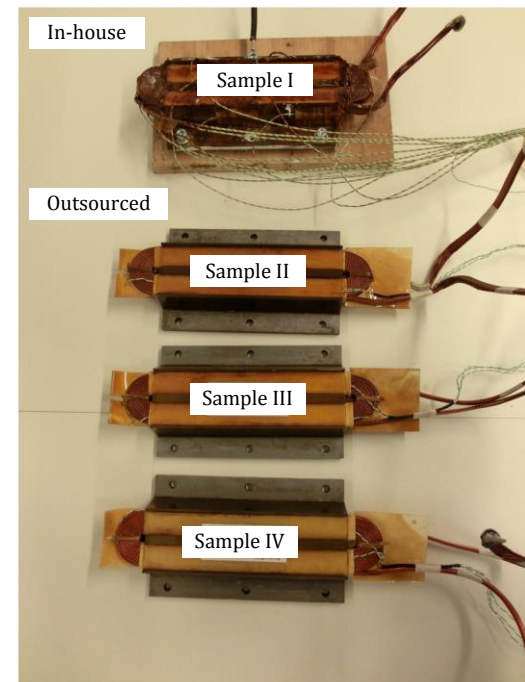


Fig. 4. Batch of motorettes with with Nomex 410 slot liner

and assembly process. Four samples built using the same materials and process has been manufactured, Fig. 4. Sample I has been prototyped in-house, whereas a batch of samples II-IV have been outsourced and manufactured by a machine manufacturing company. To reduce temperature measurement uncertainty, a multiple type-K thermocouple arrangement has been used and the measured data for a given motorette region has been averaged. It is worth mentioning that the overall temperature measurement uncertainty is set by the accuracy of

the type K-thermocouples used and is equal to $\pm 1.5^\circ\text{C}$ over the operating temperature range (-50°C to $+260^\circ\text{C}$).

IV. THERMAL ANALYSIS

To provide a more detailed insight into the conduction heat transfer from the winding body to the stator core pack, a number of thermal analyses have been performed. A thermal finite element analysis (FEA) has been used here, with the solution region reduced to a half of the motorette's cross-section, Fig. 5. The end-winding region, which is frequently associated with location of the winding hot-spot [11]-[18], is not accounted for in the theoretical investigation. Such model definition has been assumed based on symmetries in flow paths for the heat flux and thermal tests on a number of exemplar assemblies. The experimental results have shown negligible temperature difference between the active and end winding regions, consequently the two-dimensional (2D) modelling approach has been found sufficient for the analysis.

The motorette's winding is represented in the model as a homogenous region with the composite material thermal properties derived from tests on representative materials samples, Fig. 5. A complete set of thermal conductivities assumed in the analysis is listed in Table II. It is important to note that as the temperature distribution at thermal equilibrium is of interest in this investigation, the required material thermal data is limited to thermal conductivity only. The construction of material samples and testing procedure used to derive composite material properties is analogous to that presented in [10]. The interfacing surface of the motorette assembly model is set with a fixed temperature boundary condition, 15°C , whereas the remaining model surfaces are adiabatically insulated. The model definition assumes that the main heat extraction is provided by conduction from the heat source (winding) to the heat sink (cold-plate).

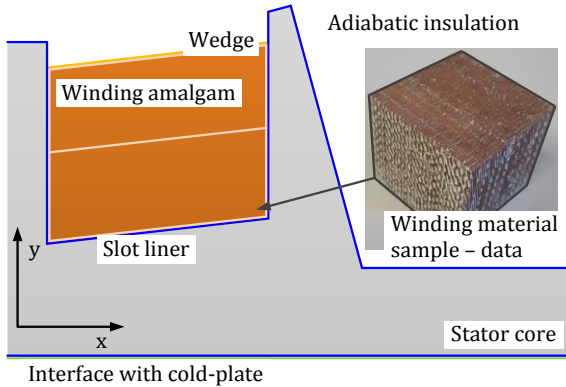


Fig. 5. Thermal model representation of the motorette assembly

TABLE II. THERMAL CONDUCTIVITY DATA ASSUMED IN THE FEAs

Model sub-region	k_x [W/m·K]	k_y [W/m·K]
Winding amalgam	1.4	1.7
Stator core	22.0	22.0
Wedge	0.3	0.3

Refer to Table I for the manufacturer provided thermal conductivity data for the analysed slot liner materials

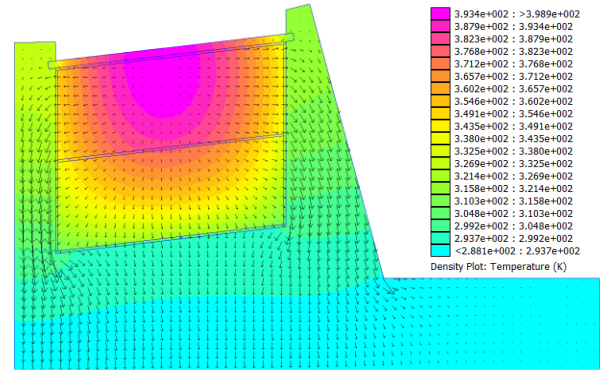


Fig. 6. An example of temperature distribution and heat flux paths within the motorette assembly from FEA

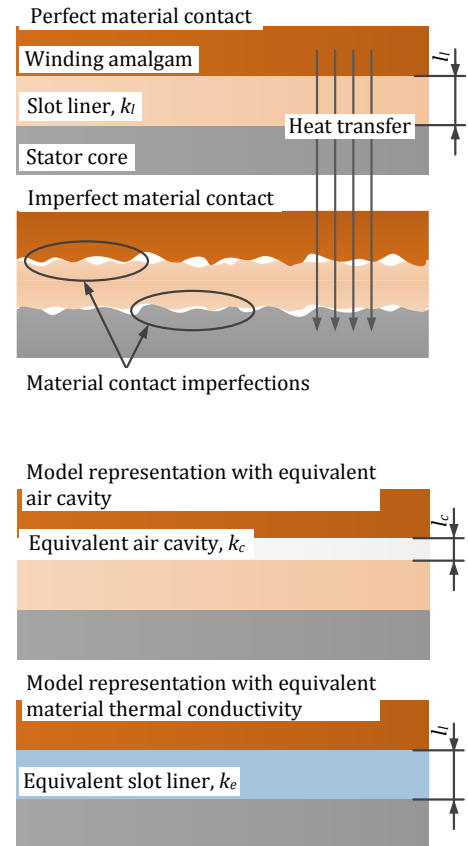


Fig. 7. Schematic explanation of material perfect and imperfect contact together with equivalent model representation

Fig. 6 shows an example output from thermal FEA illustrating the modelled temperature distribution and heat flux paths within the motorette assembly. When comparing the top and bottom layers of the winding body it is evident that low thermal resistance, 'good' heat transfer path from the winding assembly to the stator core, is essential in assuring required dissipative power loss capability. The top layer of the winding is at higher temperature than the bottom one due to a 'poorer' heat transfer path (higher equivalent thermal resistance). In this case, it is caused by less equivalent contact surface area between the winding and stator core for the top winding layer.

It is important to note that the equivalent contact surface between assembly regions depends on the geometrical contact surface area as well as ‘quality’ of the contact, which is affected by various manufacture and assembly nuances.

In the FEA models, the representation of the stator/winding assembly assumes perfect contact between model sub-regions. The temperature predictions from such models are likely to be underestimated compared with experimental data from tests on equivalent hardware exemplars. The discrepancy is likely to be a result of imperfect contact between various assembly sub-regions, which introduces an additional thermal resistance in the heat transfer path. Fig. 7 present a schematic illustration of the material contact issue, indicating irregular cavities between various stator/winding sub-regions. The interface between winding, slot liner and stator core pack has been shown to have a significant impact on the heat transfer from the winding body and consequently a machine’s power output capability [15], [16], [19]. A good understanding of the interface thermal resistance between various sub-regions is therefore necessary for accurate thermal design and machine performance predictions. Here, an approach based on experimental calibration of the mathematical models has been adopted. Fig. 7 shows correspondent model definitions accounting for the contact imperfections including the equivalent air cavity region and equivalent slot linear region. In this analysis the latter approach has been adopted with model calibration performed by adjusting thermal conductivity for the equivalent slot liner region to account for the manufacture and assembly imperfections. The resultant thermal resistance across the slot liner is a sum of two components:

$$R_l = \frac{l_l}{k_{lA}} + \frac{l_c}{k_{cA}} = \frac{l_l}{k_e A}, \quad (1)$$

where l and A refer to thickness and surface area respectively, across which the heat is transferred and k is the thermal conductivity, see Fig. 7.

The first term in (1) represents the liner sub-region, whereas the second term denotes an equivalent sub-region representing manufacture and assembly nuances. The resultant thermal resistance is given by the last term in (1). It is important to note that all contact imperfections between the stator/winding sub-regions are accounted for by k_e . Such an approach allows for the model geometry to remain unchanged and only material properties, k_e , for the linear sub-region are adjusted. Also, the slot liner sub-region has been subdivided into a section associated with the vertical and horizontal heat transfer, e.g. heat flow from the winding body to the stator back iron or stator teeth. It has been show in the literature that due to different conductor lay in the vertical and horizontal paths, separately adjusted k_e for both heat transfer planes is frequently required [19].

V. RESULTS

To compare dissipative heat transfer capability for various hardware samples considered in this analysis, the hot-spot winding temperature rise above the back iron (ΔT) versus winding dc power loss (P) plots have been used. This approach

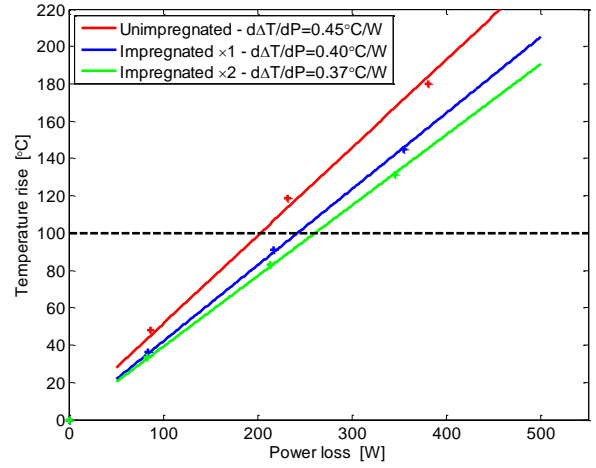


Fig. 8. Winding temperature rise above back iron vs. winding dc power loss for Nomex 410 slot liner material and varnish impregnation where appropriate

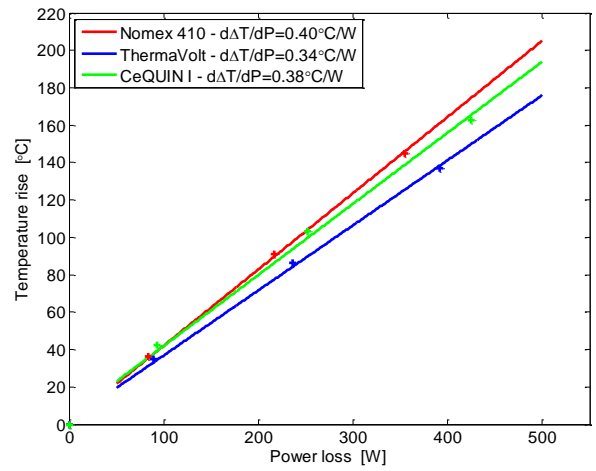


Fig. 9. Winding temperature rise above back iron vs. winding dc power loss for alternative slot liner materials and a single varnish impregnation

allows for the maximum power loss handling capability for the stator-winding assembly to be estimated. Fig. 8 presents measured results for the in-house hardware exemplar (Sample I) built with Nomex 410 slot linear at various impregnation stages: stator-winding prior to impregnation (Unimpregnated), after first impregnation (Impregnated $\times 1$) and after second impregnation (Impregnated $\times 2$). The results confirm considerable improvement in heat transfer for the doubly impregnated sample, approximately 20% improvement post-second impregnation as compared with unimpregnated sample. The rate of improvement is given here as $d\Delta T/dP$. In the context of the analysed machine and its target power output, the unimpregnated winding provides 3% margin, whereas double impregnated 20% margin to accommodate an increase in overall power loss generated within the machine stator assembly at ac operation assuming allowable 100°C winding temperature rise above the back iron.

Fig. 9 compares measured data from tests on motorette assemblies with alternative slot liner materials considered in

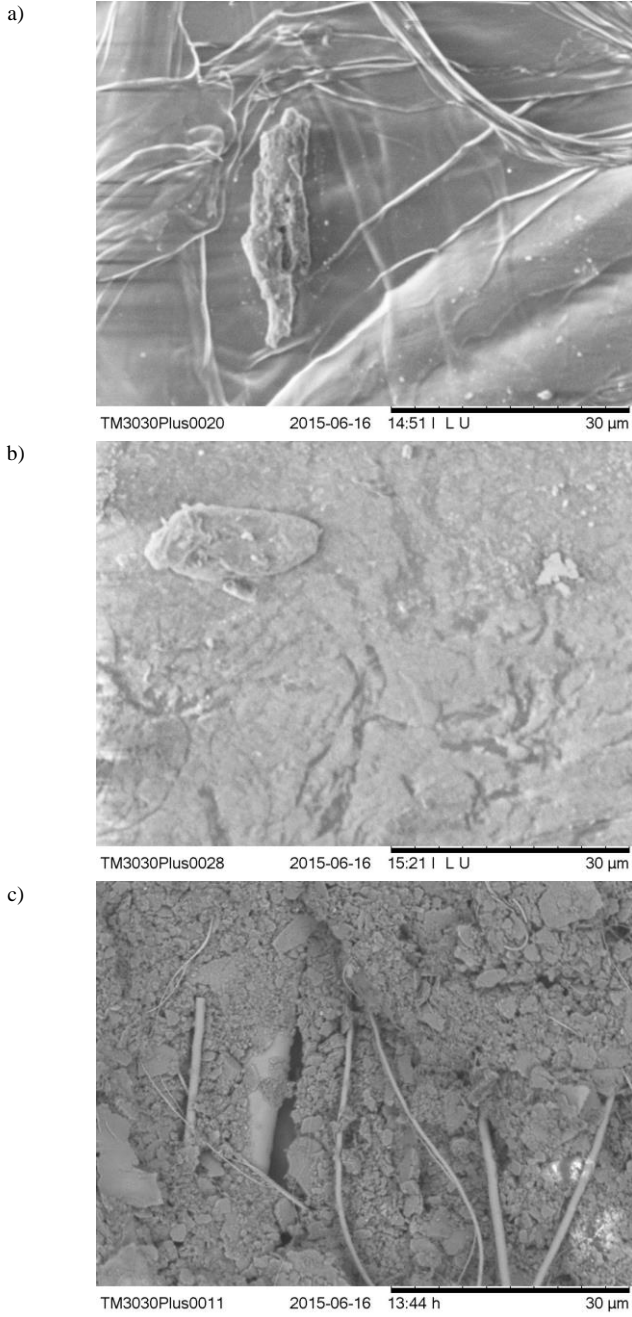


Fig. 10. Microscopic photographs of unimpregnated slot liner materials a) Nomex 410, b) ThermaVolt, c) CeQUIN I

the analysis. It is important to note that a single varnish impregnation has been used for the set of hardware exemplars tested in this investigation. The results suggests that the motorette with ThermaVolt provides the lowest thermal resistance from the winding body across into the stator core pack, whereas the exemplar with Nomex 410 provides the highest stator-winding thermal resistance among the analysed hardware samples. The rate of improvement of $d\Delta T/dP$ for the extremities is equal to 17%. It is interesting to note that the overall thermal behaviour of the analysed motorette assemblies follow a trend set by the material thermal conductivity data listed in Table I. The ThermaVolt slot liner has the highest

thermal conductivity and consequently provides the lowest thermal resistance across the stator-winding interface with CeQUIN I next and Nomex 410 the last.

Fig. 10 provides an insight into microscopic structure of the analysed slot liner materials. It is evident that CeQUIN I has the most porous construction as compared with Nomex 410 and ThermaVolt. The individual elements of the CeQUIN I material composition are prominent and include fibres of glass, microfibrils and fillers [20]. The material structure for Nomex 410 and ThermaVolt does not have visible cavities and consequently results in a more impermeable/less absorbent material structure.

Before the thermal tests, it was expected that the motorette assembly with CeQUIN I might assure the best thermal behaviour due to slot liner superior impregnation absorption. However, the experimental data suggests otherwise. This might be attributed to the impregnation material used, which in case of solvent-based varnish provides relatively low thermal conductivity as compared with alternative epoxy-resin impregnation solutions [11], and consequently does not contribute to improvement of post-impregnation liner material properties. Also, the manufacture and assembly factors affecting the individual hardware samples in a different manner might have had an impact on the thermal behaviour and overall outcome of this comparison.

To provide an insight into the manufacture and assembly issue the experimental work has been supplemented with theoretical analysis. All three motorette samples have been

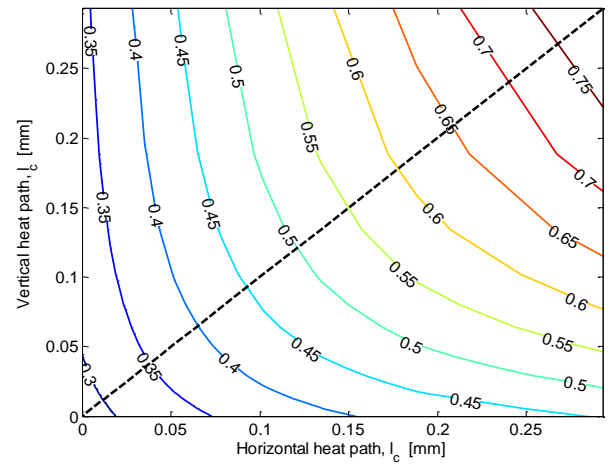


Fig. 11. Contour plot of $d\Delta T/dP$ vs. cavity thickness l_c for the vertical and horizontal heat paths – model representation of motorette assembly with Nomex 410 slot liner

TABLE III. EQUIVANET THERMAL CONDUCTIVITY AND CAVITY THICKNESS DATA

Property	Nomex 410 (Dupont)	ThermaVolt (3M)	CeQUIN I (3M)
Equivalent thermal conductivity k_e [W/m·K]	0.046	0.067	0.053
Air-gap cavity thickness l_c [mm]	0.06	0.05	0.06

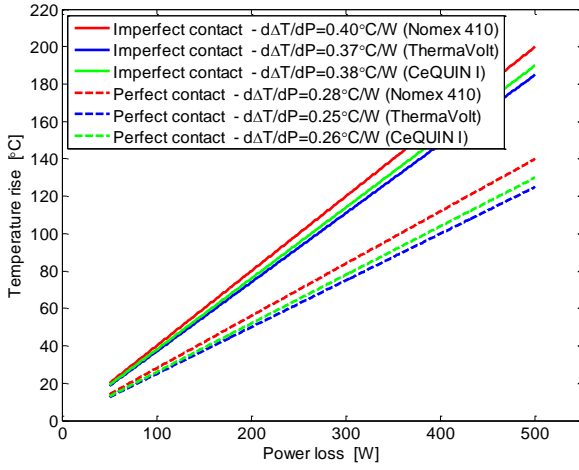


Fig. 12. Winding temperature rise vs. dc power loss for alternative slot liner materials – experimentally adjusted results to account for the same contact air-gap cavity (imperfect contact) and theoretical results (perfect contact)

analysed using the approach described in the previous section. A number of FEA simulations for perfect and imperfect contact between stator/winding sub-regions have been performed. The FE models with imperfect thermal properties have been calibrated using the experimental data. Fig. 11 presents an example of contour plot of $d\Delta T/dP$ versus equivalent cavity thickness, l_c , associated with heat transfer from the winding body into the stator core pack across the slot liner, see (1). It has been assumed here that thermal conductivity for the cavity region, k_c , is equal to that of air, $0.0181\text{W/m}\cdot\text{K}$. When inspecting the calculated results, it is evident that there are a number of alternative combinations of l_c in the horizontal and vertical heat paths assuring a match for the calculated and measured $d\Delta T/dP$. For example, in order to calibrate the model with Nomex 410 slot liner ($d\Delta T/dP = 0.40^\circ\text{C/W}$) we could assume perfect contact for the vertical heat path and 0.16mm cavity for the horizontal path or 0.04mm cavity in the horizontal path and 0.31mm cavity in the vertical path for the extremities. This unambiguity is caused by the limited number of temperature measuring points used during tests on the motorette samples. A higher fidelity, resolution temperature measurements and/or supplementary tests would allow for a more definite calibration approach. Due to insufficient number temperature measuring points, it has been assumed in the analysis that the equivalent thermal conductivity, k_e , is identical for both the horizontal and vertical heat paths, as shown by the dashed line in Fig. 11.

Table III includes adjusted thermal conductivity, k_e , for the slot liner region and equivalent air-gap cavity thickness, l_c . The results suggest that motorette assembly with ThermaVolt slot liner has better built factor resulting in smaller stator-to-winding air-gap cavity as compared with other motorette exemplars. To make the comparison between the slot liner materials clearer, the results for ThermaVolt have been adjusted for the same 0.06mm air-gap cavity using the FEA thermal model. Fig. 12 shows results for all the liner materials for perfect and imperfect contact between winding body and stator core assembly. It is worth recalling that the imperfect

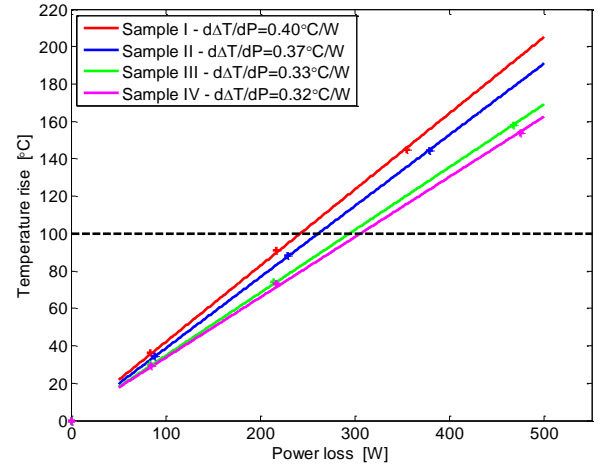


Fig. 13. Winding temperature rise vs. dc power loss for a batch of motorettes with Nomex 410 slot liner material and varnish impregnation

contact refers to the experimentally calibrated FE models adjusted for the same air-gap cavity. As expected the adjusted results for ThermaVolt indicate lower rate of improvement as compared with experimental data, 0.37°C/W and 0.34°C/W respectively, Figs. 9 and 12. The general trend in terms of $d\Delta T/dP$ for the analysed linear materials remains unchanged.

To provide and insight into the manufacture and assembly related issues and their impact on the motorette's thermal behaviour, a batch of supplementary motorette samples has been manufactured by an external electrical machine manufacturing company. The materials, manufacture and assembly processes employed were identical to that used for the in-house built prototypes. The batch of motorettes considered here has been manufactured using Nomex 410 slot liner and single varnish impregnation. Fig. 13 presents experimental data from tests on the set of motorettes (Sample II - IV) together with results for the in-house built exemplar (Sample I). The data indicates a degree of discrepancy between the samples with 8% to 25% $d\Delta T/dP$ variation when comparing the in-house manufactured and outsourced samples, and up to 15% for the outsourced samples only. It is evident that a non-negligible degree of discrepancy between alternative motorette samples exists, which in the context of complete machine assembly has important implications, i.e. undesirable non-uniform temperature/hot spots distribution around the winding circumference. As a number of analysed motorette samples is relatively small, it is difficult to draw any more comprehensive conclusions regarding repeatability of the manufacturing and assembly processes used in construction of the motorettes. A statistics based approach making use of a larger batch of test samples would be more informative/appropriate here. Further work is required to identify the particular manufacture and assembly deficiencies/nuances affecting thermal behaviour for the analysed machine/stator-winding constructions.

VI. CONCLUSIONS

This paper investigates the use of alternative slot liner materials commonly employed in construction of electrical machines. The material samples used in this analysis are

characterised by a set of physical properties provided by the material manufactures, which are indicative of material applicability and performance. However, when considering a particular machine design with numerous materials, manufacture and assembly process used an 'in situ' material performance for a representative hardware exemplars (motorettes) is of particular interest. Such an approach provides an insight into behaviour of the complete machine assembly accounting for interaction between various materials and subassemblies post final manufacture. In this analysis the research focus has been placed on heat transfer from the winding body across the slot liner material into the stator core pack. The experimental results have shown that in the analysed case, with vacuum varnish impregnation, the slot liner with higher thermal conductivity assures improved transfer between the stator and winding subassemblies as compared with slot liner materials with poorer thermal properties. In this analysis, ThermaVolt has been found to be better than CeQUIN I and Nomex 410. It is important to note that the other material physical properties like mechanical strength and/or dielectric breakdown voltage also need to be considered accounting for the particular design requirements and intended manufacture and assembly processes.

The experimental work has been supplemented with theoretical analysis to assess influence of the manufacture and assembly factors on motorette thermal behaviour and provide a clearer comparison between hardware exemplars with different build 'quality'. The theoretical investigation has shown a level of unambiguity of the thermal model calibration with a reduced number experimental data points. In order to provide a more informed calibration process accounting for localised heat transfer discrepancies, a higher fidelity/higher resolution experimental approach is required. To provide an insight into the manufacture and assembly issues, tests on a batch of motorette samples built using the same materials and processes have been performed. The experimental findings indicate a degree discrepancy between the samples, which is undesirable in the context of complete machine assembly with fluctuation in thermal behaviour for the individual winding's coils. Further work is required to identify the manufacture and assembly nuances affecting the winding-to-winding heat transfer. Experimental tests using a statistically relevant sample size of motorettes would provide more robust approach to account for natural variations in manufacture and assembly.

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REFERENCES

- [1] P. Arumugam, T. Hamiti, C. Gerada, "Modeling of Different Winding Configurations for Fault-Tolerant Permanent Magnet Machines to Restrain Interturn Short-Circuit Current," *IEEE Transactions on Energy Conversion*, vol. 27, no. 2, pp. 351 – 361, June 2012.
- [2] R. Wrobel, A. Mlot, P. H. Mellor, "Contribution of End-Winding Proximity Losses to Temperature Variation in Electromagnetic Devices," *IEEE Transactions on Industrial Electronics*, vol. 59, pp. 848–857, February 2012.
- [3] S. Iwasaki, R. P. Deodhar, L. Yong, A. Pride, Z. Q. Zhu, "Influence of PWM on Proximity Loss in Permanent-Magnet Brushless AC Machines," *IEEE Transactions on Industry Applications*, vol. 45, pp. 1359–1367, July/August 2009.
- [4] R. Wrobel, A. Griffio, P. H. Mellor, "Derivation and Scaling of AC Copper Loss in Thermal Modeling of Electrical Machines," *IEEE Transactions on Industrial Electronics*, (early access article).
- [5] P. B. Reddy, T. M. Jahns, "Analysis of Bundle Losses in High Speed Machines," *International Conference on Power Electronics*, 2010, IPEC'10, pp. 2181–2188.
- [6] P. H. Mellor, R. Wrobel, McNeill, "Investigation of Proximity Losses in a High Speed Brushless Permanent Motor," *41st IAS Annual Meeting, IEEE Industry Applications Conference*, 2006, vol. 3, pp. 1514 – 1518, September 2006.
- [7] L. J. Wu, Z. Q. Zhu, D. Staton, M. Popescu, D. Hawkins, "Analytical Model of Eddy Current Loss in Windings of Permanent-Magnet Machines Accounting for Load," *IEEE Transactions on Magnetics*, vol. 48, no. 7, pp. 2138 – 2151, July 2012.
- [8] Y. Amara, P. Reghem, G. Barakat, "Analytical Predictions of Eddy-Current Loss in Armature Winding of Permanent Magnet Brushless AC Machines," *IEEE Transactions on Magnetics*, vol. 46, no. 8, pp. 3481 – 3484, August 2010.
- [9] H. Hamalainen, J. Pyrhonen, J. Nerg, "AC Resistance Factor in One-Layer Form-Wound Winding Used in Rotating Electrical Machines," *IEEE Transactions on Magnetics*, vol. 49, no. 6, pp. 2967 – 2973, June 2013.
- [10] N. Simpson, R. Wrobel, P. H. Mellor, "Estimation of Equivalent Thermal Parameters of Impregnated Electrical Windings," *IEEE Transactions on Industry Applications*, vol. 49, no. 6, pp. 2505 – 2515, November – December 2013.
- [11] R. Wrobel, P. H. Mellor, D. Holliday, "Thermal Modelling of a Segmented Stator Winding Design," *IEEE Transactions on Industry Applications*, vol. 47, no. 5, pp. 2023 – 2030, September – October 2011.
- [12] R. Wrobel, P. H. Mellor, N. McNeill, D. A. Staton, "Thermal Performance of an Open-Slot Modular-Wound Machine with External Rotor," *IEEE Transactions on Energy Conversion*, vol. 25, no. 2, pp. 403 – 411, June 2010.
- [13] W. Boughamni, J.-P. Manata, S. Ait-Amar, D. Roger, "Electrical Machines Insulation: Towards Low Environmental Impact Solutions," *IEEE International Conference on Solid Dielectrics*, 2013, (ICSD 20013), pp. 557 – 560.
- [14] J. Richnow, P. Stenzel, A. Renner, D. Gerling, C. Endisch, "Influence of Different Impregnation Methods and Resins on Thermal Behaviour and Lifetime of Electrical Stators," *4th International Electric Drives Production Conference*, 2014, (EDPC 2014), pp. 1 – 7.
- [15] A. Boglietti, A. Cavagnino, D. Staton, "Determination of Critical Parameters in Electrical Machine Thermal Models," *IEEE Transactions on Industry Applications*, vol. 44, no. 4, pp. 1150 – 1159, July – August 2008.
- [16] A. Boglietti, A. Cavagnino, M. Popescu, D. Staton, "Thermal Model and Analysis of Wound-Rotor Induction Machine," *IEEE Transactions on Industry Applications*, vol. 49, no. 5, pp. 2078 – 2085, September – October 2013.
- [17] M. Galea, C. Gerada, T. Raminosa, P. Wheeler, "A Thermal Improvement Technique for the Phase Windings of Electrical Machines," *IEEE Transactions on Industry Applications*, vol. 49, no. 5, pp. 79 – 87, January – February 2012.
- [18] A. M. El-Refaie, J. P. Alexander, S. Galioto, P. Reddy, H. Hum-Kang, P. de Bock, S. Xiochun, "Advanced High Power-Density Interior Permanent Magnet Motor for Traction Applications," *IEEE Transactions on Industry Applications*, vol. 50, no. 5, pp. 3253 – 3248, September – October 2014.
- [19] J. Baker, R. Wrobel, D. Drury, P. H. Mellor, "A Methodology for Predicting the Thermal Behaviour of Modular-Wound Electrical Machines," *IEEE Energy Conversion Congress and Exposition, (ECCE2014)*, pp. 5176–5183, September 2014.
- [20] <http://www.dicamit.it/> (Date viewed: 29/06/2015)
<http://www.dupont.com/> (Date viewed: 29/06/2015)